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Final Report: Spectral Analysis of L-shell Data in the Extreme Ultraviolet from Tokamak Plasmas

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February 5, 2016

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This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

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P.I.: J. Garrett Jernigan, University of California Space Sciences Laboratory

Final Report

We performed detailed analyses of extreme ultraviolet spectra taken by Lawrence Livermore National Laboratory on the National Spherical Torus Experiment at Princeton Plasma Physics Laboratory and on the Alcator C-mod tokamak at the M.I.T. Plasma Science and Fusion Center. We focused on the emission of iron, carbon, and other elements in several spectral band pass regions covered by the Atmospheric Imaging Assembly on the Solar Dynamics Observatory. We documented emission lines of carbon not found in currently used solar databases and demonstrated that this emission was due to charge exchange.

Publications:

Measuring plasma impurities in Alcator C-Mod as a function of time in the extreme ultraviolet.
P. Beiersdorfer, G.V. Brown, J.B. Kamp, E.W. Magee, J.K. Lepson, Y. Podpaly, and M.L. Reinke, Canadian Journal of Physics 89: 653–656 (2011)

High-resolution time-resolved extreme ultraviolet spectroscopy on NSTX.
J. K. Lepson, P. Beiersdorfer, J. Clementson, M. Bitter, K. W. Hill, R. Kaita,
C. H. Skinner, A. L. Roquemore, and G. Zimmer, Review of Scientific Instruments 83, 10D520 (2012)

*Emission lines of iron in the 150-250 Å region on National Spherical Torus Experimen*t.

J. K. Lepson, P. Beiersdorfer' M. Bitter, A. L. Roquemore, and R. Kaita, Physica Scripta, 156: 014075 (2013)

Charge exchange produced emission of carbon in the extreme ultraviolet spectral region.
J. K. Lepson, P. Beiersdorfer, M. Bitter, A. L. Roquemore, K. Hill, and R. Kaita.
Journal of Physics: Conference Series, 583: 012012 (2015)

Unusual emission lines of carbon in the 170-190 Å region on NSTX.
J. K. Lepson, P. Beiersdorfer, M. Bitter, A. L. Roquemore, and R. Kaita.
AIP Conference Series, *in press*.

Invited Talks:

22 July 2011: *Laboratory Calibration of Density-Dependent Lines in the Extreme Ultraviolet Spectral Region*, 17th International Conference on Atomic Processes in Plasmas, Belfast, Northern Ireland.

09 October 2013: *Identification of Charge-Exchange Produced Lines of Carbon in the Iron M-Shell Spectrum on NSTX*, 18th International Conference on Atomic Processes in Plasmas, Auburn, AL.

Contributed Talk:

September 2014, *Charge-Exchange Produced Emission of Carbon in the Extreme Ultraviolet Spectral Region*, 17th International Conference on the Physics of Highly Charged Ions, San Carlos de Bariloche, Argentina.

Poster Presentations:

November 2011: *High-Resolution Time-Resolved Extreme Ultraviolet Spectroscopy on NSTX*, Division of Plasma Physics of the American Physical Society, Salt Lake City, UT.

May 2012: *High-Resolution Time-Resolved Extreme Ultraviolet Spectroscopy on NSTX*, High Temperature Plasma Diagnostics, Monterey, CA.

September 2012: *Emission Lines of Iron in the 170-200Å Region*, 16th International Conference on the Physics of Highly Charged Ions, Heidelberg, Germany.

Spectral Analysis of L-shell Data in the Extreme Ultraviolet from Tokamak Plasmas

P.I.: J. Garrett Jernigan, University of California Space Sciences Laboratory

Progress Report: June 1, 2013– December 31, 2014

We performed detailed analyses of extreme ultraviolet spectra taken by Lawrence Livermore National Laboratory on the National Spherical Torus Experiment at Princeton Plasma Physics Laboratory and on the Alcator C-mod tokamak at the M.I.T. Plasma Science and Fusion Center. During the period covered by this progress report, we focused on emission of iron, carbon, and other elements in several spectral band pass regions covered by the Atmospheric Imaging Assembly on the Solar Dynamics Observatory. We documented emission lines of carbon not found in currently used solar databases and demonstrated that this emission was due to charge exchange.

Lepson presented an invited talk on the carbon charge exchange lines at the 18th International Conference on Atomic Processes in Plasmas and submitted a paper that was accepted for publication (attached below), as well as a contributed talk at the 17th International Conference on the Physics of Highly Charged Ions (paper attached below).

Unusual emission lines of carbon in the 170-190 Å region on NSTX

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Abstract.
We measured the spectral emission of plasmas from the National Spherical Tokamak Experiment in the extreme ultraviolet region, typically dominated by M-shell iron lines. Although we found that most of the significant emission in the 170–270 Å region emanates from iron, there are also some strong lines of carbon present. We show that the carbon lines are not produced by electron-impact excitation, and we speculate that they are formed instead by charge exchange.

Keywords: atomic processes – line: identification – techniques: spectroscopic
PACS: 32.30.Jc,52.25.Vy,52.55.Fa,52.70.-m

INTRODUCTION

Charge exchange is an important process in astrophysics. Charge exchange occurs extensively in the solar system, e.g., in the interaction of neutral atoms of cometary comae and planetary atmospheres with the highly charged solar wind [1, 2, 3, 4]. It may also be a significant source of soft x rays in such objects as supernova remnants and starburst galaxies [5, 6]. Charge exchange is also known to occur in a variety of such terrestrial plasmas, such as tokamaks [7, 8, 9].

The search for astrophysical charge exchange phenomena has so far mainly focused on the x-ray emission of K-shell ions [1, 10, 11] because of the available detection systems currently in orbit. Identifying lines produced by charge exchange in other spectral bands may accelerate the search for this cosmic line formation process. The extreme ultraviolet region is of particular interest because both the *Chandra* and *XMM-Newton* x-ray observatories are sensitive to emission in this region from cosmic sources. Moreover, the *Hinode* satellite and the *Solar Dynamics Observatory* observe this spectral band in the sun.

In the following, we report on lines of carbon in the 170–215 Å region that cannot be explained by collisional excitation. Based on concurrent measurements of the C V and C VI K-shell emission lines, we suggest that these are produced by charge exchange.

METHODS

We obtained time-resolved spectra on NSTX using the time-resolving Long-Wavelength EUV Spectrometer (LoWEUS) instrument [12]. LoWEUS is a flat-field grating spectrometer with variable line spacing and a mean 1200 ℓ/mm, based on a design originally used at the Livermore electron beam ion trap [13, 14]. The spectral resolution is ∼0.3 Å, resulting in a resolving power $\lambda/\Delta\lambda$ ∼500–800 in the 150–250 Å region we examined. LoWEUS had a time resolution of ∼13 ms at the time (since then upgraded to ∼5 ms [15]), enabling examination of impurity evolution over the duration of the shot, as well as better correlation of emission with plasma conditions as measured by multi-point Thomson scattering (e.g., Fig. 1 in [15]). Our group has also installed similar instruments on the Alcator tokamak [16, 17].

The iron emission observed in this region was compared to modeling calculations using the CHIANTI database (v. 7.0 [18, 19]). Good agreement was found, similar to that reported in [20, 21], and we do not repeat such fits here. Calculations of the carbon line emission from collisional excitation were performed using the Flexible Atomic Code [22]. The line emission was calculated for the temperature of maximum abundance for C V (31 eV) and C VI (87 eV),

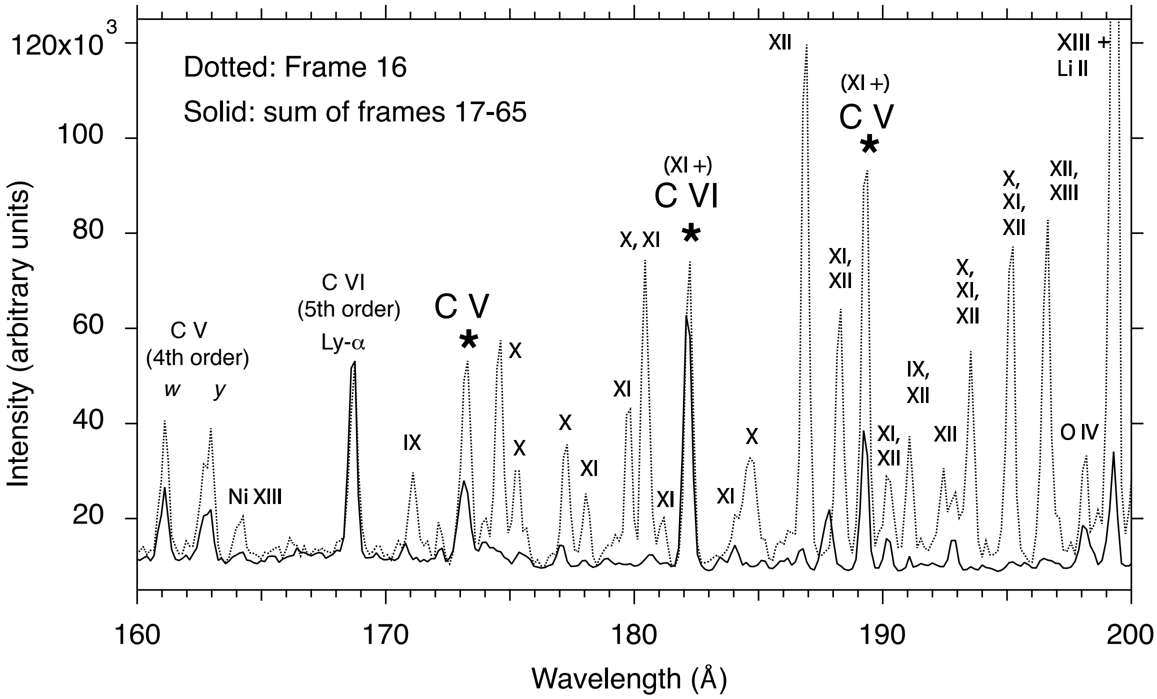

FIGURE 1. Spectrum of NSTX Shot 14111 taken by LoWEUS at different times. Strongest iron lines are identified by charge state. Dotted line: ~200 ms into the shot. Strong, non-iron features are indicated by asterisks associated with CV and C VI. Solid line: summation of the temporal emission of the remainder of shot (40 frames, ~220–800 ms). The roman numerals denote the spectral number of iron forming a given peak.

using an electron density $N_e = 5 \times 10^{13}\text{cm}^{-3}$. Calculations at higher and lower densities were also performed, but no effect of density on the relative line emission could be seen.

RESULTS

We present data from NSTX shot 141111, taken on 16 Sept 2010. Iron and, to a lesser extent, nickel are present as impurities in some shots that may be due to sputtering of stainless steel components in the tokamak vessel. M-shell iron emission, when present, occurs during the beginning of the shot, typically in the first 10–100 ms, when the electron temperature of the plasma is ~100–300 eV. Shot 141111 unexpectedly included a second iron emission period ~170–220 ms into the shot, when T_e reached 500–750 eV. In Fig. 1, we show emission from ~200 ms into the shot, when T_e ~750 eV and $N_e \sim 4 \times 10^{13}\text{cm}^{-3}$, overlaid with emission from the remainder of the shot. The remainder of the shot, which represents the sum of the emission between 220 and 800 ms, displays very little iron emission.

Figure 2 (a) shows the full view of the spectrum in Fig. 1, together with the calculated emission of C V under collisional excitation overlaid. The calculations show the helium-like lines commonly known as w and y in 1st order, while the spectrum has these lines in 3rd and 4th order. Line intensities were normalized by using the strength of w and y in 3rd order compared to 1st order. For this, a measurement of the grating efficiency for measuring the carbon line in different orders was made at the EBIT-I machine [23] at Lawrence Livermore National Laboratory (not shown).

DISCUSSION

All significant iron emission in the NSTX plasma observed by LoWEUS, ranging from Fe VIII through Fe XV, could be identified with the CHIANTI atomic database, in accordance with earlier such analyses [20, 21]. The iron M-shell emission typically ceases to be visible after 100 ms into the discharge, when $T_e > 500$ eV. The lack of iron M-shell emission after this time can be attributed to the fact that the observable ionization balance favors L-shell iron ions, i.e.

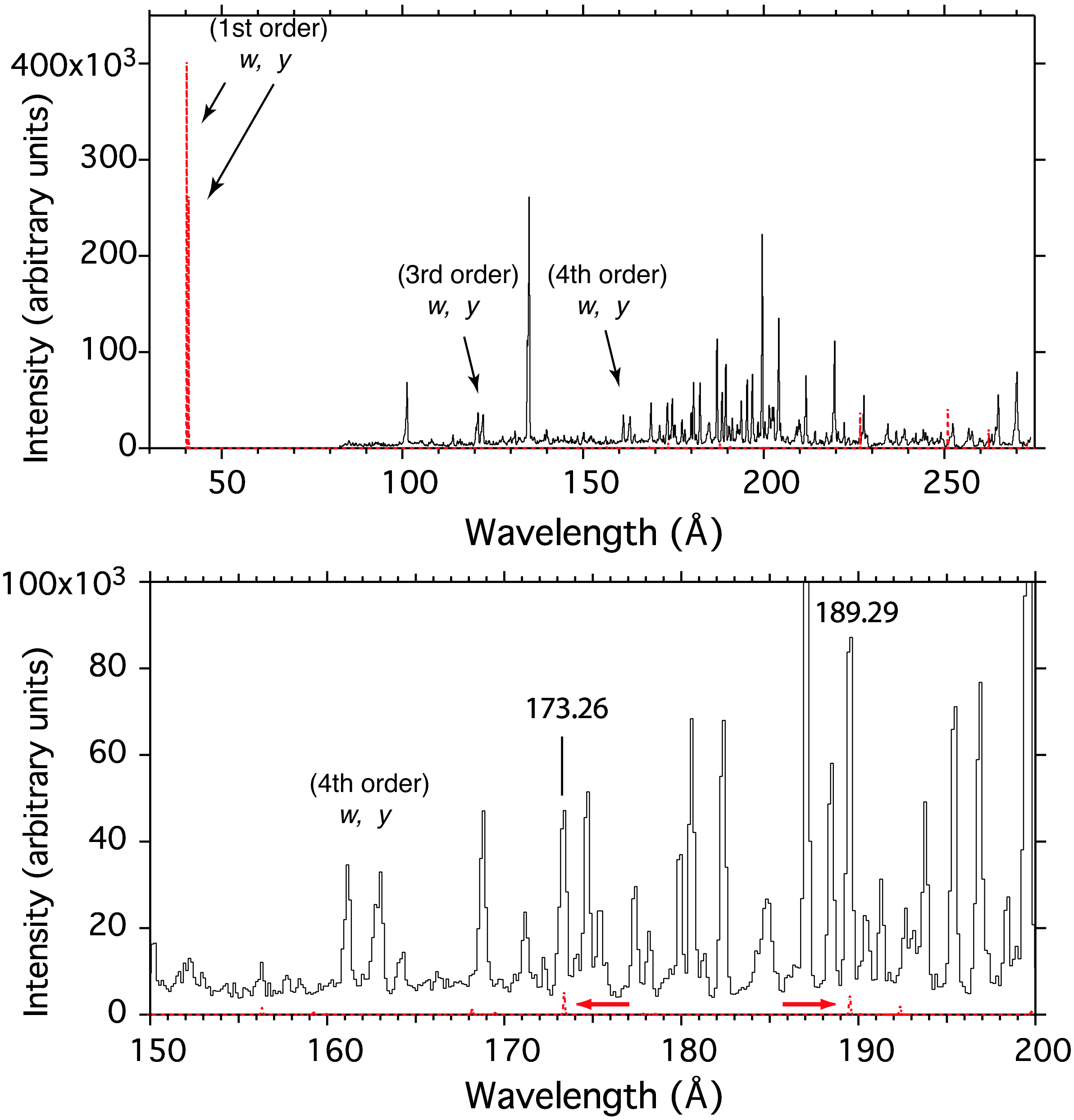

FIGURE 2. Emission of helium-like C V from collisional excitation, as calculated with the Flexible Atomic Code (dashed line), overlaid onto the LoWEUS spectrum of NSTX (solid line). Line intensities were calibrated by using the strength of lines *w* and *y* observed in 3rd order as compared to 1st order measured with EBIT-I. (top) Full spectrum, showing lines *w* and *y* in 1st order (calculated) and 3rd order (measured). (bottom) inset showing calculated vs. measured lines. Two strongest calculated lines are marked with arrows. Color version online.

Fe XVIII – Fe XXIV, which emit at lower wavelengths than covered by LoWEUS, and to a dearth of new iron influx from the vessel wall. Resumption of iron M-shell emission in this shot is attributed to an influx of cold iron from the plasma edge, probably from plasma striking the wall or an in-vessel hardware component.

Several strong features appear at this time (marked by asterisks in Fig. 1), which we have identified as emission of C V and C VI [24]. The newly observed carbon emission lines were not present in the CHIANTI astrophysical spectral database, but lines at the appropriate position were found in either the NIST (v4, [25]) or Kelly [26] databases. Suppport for the hypothesis that these lines are emitted by carbon is also seen in Fig. 1, which overlays the emission at $\sim$200 ms (dotted line) with emission of the remainder of the shot ($\sim$220–800 ms, solid line). Relative intensities of the new lines closely track those of the well known K-shell linee of C V and C VI, which appear in higher order in the LoWEUS spectra.

These new emission lines of carbon are unlikely to be due to collisional excitation. Their strengths, calculated in our FAC models based on electron-impact excitation and seen in Fig. 2, are vanishingly small. Their absence from CHIANTI is therefore not surprising because CHIANTI relies on collisional excitation to form the lines in its data set.

We propose that the strength of the new C V and C VI lines in our spectrum are indicative of non-equilibrium processes. In particular, charge exchange of highly charged carbon with neutral hydrogen is a likely candidate process.

Charge exchange populates preferentially levels with principal quantum number n_c given by $n_c \approx q^{3/4}$ where q is the charge of the capturing ion (c.f. review by Wargelin et al. [27]). For C^{5+} and C^{6+} ions we have n_c = 3.3 and n_c = 3.8, respectively. Thus, this process mainly affects the population of the $n = 3$ and $n = 4$ levels in carbon, and our strongest lines, at 173.19 and 189.40 Å are both 4→2 transitions, while the feature at 182.23 Å is a blend of 3→2 transitions. Neutral deuterium was injected into the plasma in form of energetic beams for core plasma heating when these lines were seen. In addition, neutrals enter the plasma as recycled deuterium along the vessel wall. For example, charge exchange between helium-like Ar XVII and neutral hydrogen has been observed in the x ray region near the vessel wall at the Alcator tokamak [28].

Collisional excitation preferentially populates the singlet level so that line w is almost twice the strength of line y, whereas charge exchange preferentially populates the triplet levels so that line y is as strong or stronger than line w [9, 27]. (Note that line z is populationally de-excited, adding to the intensity of y, and it is not seen at the densities found in NSTX.) The relative strengths of the C V line pair w and y seen here (c.f. Fig. 2 bottom, where the lines are seen in 4th order) are in line with being produced in part by charge exchange and, thus, are diagnostic of charge exchange. Calculations of charge exchange in helium-like and hydrogenic carbon are ongoing and will be presented in future work.

ACKNOWLEDGMENTS

This work was supported by the DOE General Plasma Science program. Work was performed by Lawrence Livermore National Laboratory and Princeton Plasma Physics Laboratory under the auspices of the U. S. Department of Energy under Contracts DEAC52-07NA27344 and DE-AC02-09CH11466. CHIANTI is a collaborative project involving George Mason University, the University of Michigan (USA) and the University of Cambridge (UK).

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Charge exchange produced emission of carbon in the extreme ultraviolet spectral region

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Abstract.
We used a time-reolving high-resolution grating spectrometer to study extreme ultraviolet emission from plasmas in the National Spherical Tokamak Experiment (NSTX). The NSTX spectral range from 150-250 Å is typically dominated by emission from M-shell iron lines, L-shell transitions of oxygen, or K-shell lines of lithium. However, we also observed several intense emission lines, which we now attribute to transitions in C V and C VI. Collisional-radiative modeling shows that electron-impact excitation is far too weak to account for the features we observed. Instead, these lines appear to be produced by charge exchange with neutral hydrogen.

1. Introduction

Charge exchange occurs when an ion takes an electron from a neutral species or from an ion with lesser charge, thereby reducing its own charge while increasing the charge of the donor species. In recent years, it has been identified as an important process in astrophysics, where it contributes to the soft x-ray background. Charge exchange occurs extensively in the solar system, e.g., in the interaction of neutral atoms of cometary comae and planetary atmospheres with the highly charged solar wind [1, 2, 3], and may also be a significant source of soft x rays in such objects as supernova remnants and starburst galaxies [4, 5]. Charge exchange is also of interest as a diagnostic tool in tokamaks, especially for determining ion temperature and impurity profiles using an energetic neutral beam to enable charge exchange deep within the plasma [6, 7, 8].

Spectral observations of astrophysical charge exchange phenomena have mainly focused on the x-ray emission of K-shell ions. Identifying lines produced by charge exchange in the extreme ultraviolet (EUV) region may aid in ascertaining charge exchange phenomena in cooler plasmas. Both the *Chandra* and *XMM-Newton* x-ray observatories are sensitive to EUV emission from cosmic sources, while the Hinode satellite and the *Solar Dynamics Observatory* observe this spectral band in the sun. Thus, it may be possible to use these currently operating observatories to search for lines indicative of charge exchange.

In recent years we have made measurements of the EUV emission spectra generated by the NSTX spherical torus [9, 10, 11]. The focus of these measurements has been to study the iron L-shell and iron M-shell emission and to calibrate density-sensitive line ratios [11, 12].

While studying the M-shell iron emission in the 170–250 Å region, we observed unexpected enhancements of some of the lines in this region, which initially appeared to be iron lines. Upon additional studies, we attributed the lines to transitions in carbon C V and C VI [15]. In the following, we present spectral data from NSTX discharges that have no noticeable iron emission. This confirms that the lines in question are not from iron. A comparison of the observed carbon emission with spectral calculations rules out that the lines are produced by electron-impact excitation. This leaves charge exchange as the production mechanism.

2. Experiment

We obtained spectra on NSTX using the Long-Wavelength EUV Spectrometer (LoWEUS; [11]) instrument. LoWEUS is a flat-field grating spectrometer with variable line spacing and a mean 1200 ℓ/mm. The spectral resolution is $\sim$0.3 Å, resulting in a resolving power $\lambda/\Delta\lambda \sim$500-800 in the 150-250 Å region we examined ([16]). LoWEUS is capable of a time resolution of $\sim$5 ms, but was operated in time-integrated mode during the shot we present here. We operate a similar instrument on the Alcator tokamak [17, 18].

Figure 1 shows a spectrum from NSTX shot 140324. The strongest line in the spectrum is the Li III $2p \rightarrow 1s$ Lyman-α transition at 133 Å. The $2p \rightarrow 1s$ emission from heliumlike Li II can be seen just below 200 Å. The other strong lines are all from carbon, i.e., the they are K-shell transitions from C V and C VI. Although these lines occur near 41 and 33 Å, respectively, they appear here in higher order diffraction. The fact that these carbon lines are seen proves the abundance of carbon in the plasma.

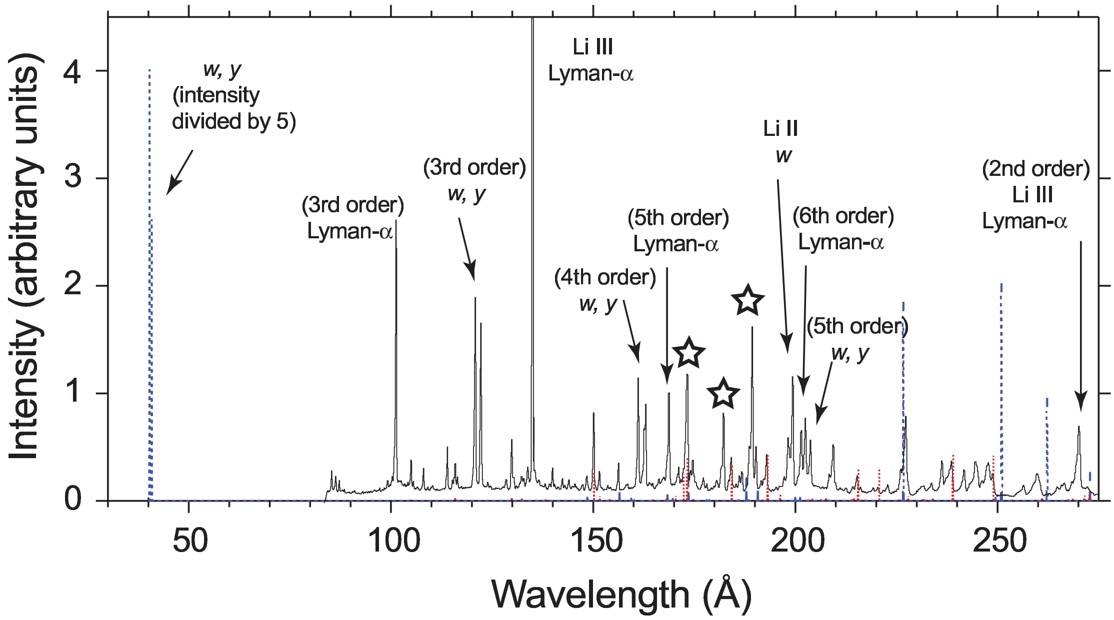

Figure 1. NSTX Shot 140324 (solid line) overlaid with FAC calculations of carbon emission due to collisonal excitation (blue dashed lines) and oxygen emission from the CHIANTI database (red dotted lines). Intensities of carbon IV lines w and y in first order have been decreased by a factor of 5 to fit on the figure. Lines not identified to element are carbon; strong new carbon lines are marked with stars.

It is interesting to note that the the K-shell spectrum of heliumlike C V is comprised of two lines, commonly known as w and y, which emanate from the upper levels $1s2p\ ^1P_1$ and $1s2p\ ^3P_1$,

Table 1. Candidate carbon lines in the 170– 250 Å region.

Ion	Wavelength (Å)	Lower Level	Upper Level
C V	173.281	$1s2s\ ^3P_1$	$1s4p\ ^3P_1$
C VI	182.088	$2p\ ^2P_{1/2}$	$3d\ ^2D_{3/2}$
C VI	182.097	$2p\ ^2P_{1/2}$	$3d\ ^2D_{3/2}$
C VI	182.132	$2p\ ^2P_{1/2}$	$3d\ ^2D_{1/2}$
C VI	182.144	$2p\ ^2P_{1/2}$	$3d\ ^2D_{1/2}$
C VI	182.230	$2p\ ^2P_{3/2}$	$3d\ ^2D_{5/2}$
C VI	182.246	$2p\ ^2P_{3/2}$	$3d\ ^2D_{3/2}$
C VI	182.290	$2p\ ^2P_{3/2}$	$3d\ ^2D_{1/2}$
C V	189.255	$1s2p\ ^3P_1$	$1s4s\ ^3S_1$
C V	189.260	$1s2p\ ^3P_0$	$1s4s\ ^3S_1$
C V	189.304	$1s2p\ ^3P_2$	$1s4s\ ^3S_1$
C V	227.190	$1s2s\ ^3S_1$	$1s3p\ ^3P_2$
C V	227.202	$1s2s\ ^3S_1$	$1s3p\ ^3P_0$
C V	227.203	$1s2s\ ^3S_1$	$1s3p\ ^3P_1$
C V	248.660	$1s2p\ ^3P_1$	$1s3d\ ^3D_2$
C V	248.660	$1s2p\ ^3P_1$	$1s3d\ ^3D_1$
C V	248.672	$1s2p\ ^3P_0$	$1s3d\ ^3D_1$
C V	248.740	$1s2p\ ^3P_2$	$1s3d\ ^3D_3$
C V	248.748	$1s2p\ ^3P_2$	$1s3d\ ^3D_1$
C V	248.748	$1s2p\ ^3P_2$	$1s3d\ ^3D_2$

respectively.

Several weaker lines can also be seen. We have not yet identified all lines, but many of the weaker lines can be attributed to oxygen. The positions and relative intensities of the oxygen lines in this wavelength band are given by the CHIANTI spectral model [19, 20], as indicated by the red dotted lines in Fig. 1.

The spectrum in Fig. 1 also shows three relatively strong features marked with an asterisk. These are the features we have recently attributed to the carbon lines listed in Table 1.

3. Comparison with Theoretical Spectra

Calculations of the carbon line emission from collisional excitation were performed using the Flexible Atomic Code [21]. The line emission was calculated for the temperature of maximum abundance for C V (31 eV) and C VI (87 eV), using the electron density $n_e = 5 \times 10^{13}\mathrm{cm}^{-3}$ measured by Thomson scattering. Calculations with higher and lower densities were also performed, but an effect of the density on the relative line emission could not be seen unless the density was varied by several orders of magnitude.

The results from our calculations for C V are shown in Fig. 1 as blue dashed traces. Here, we also show the w and y lines in 1st order. These lines appear in the spectrum only in 3rd and higher orders. We have normalized the intensity of the calculated emission in 1st order to the observed emission in 3rd order with the help of a measurement of the grating efficiency for measuring the w line in different orders made at the EBIT-I machine [22]. Because the first-order w and y lines are much stronger than the higher orders we observed, the NSTX spectrum and the calculated lines in the region we observed have been expanded vertically by a factor of 5 in order to better see the lines.

Our calculations predict several C V lines that fall into the observed spectral range. The largest predicted lines are near 228 and 251 Å, and they are stronger than any of the observed features. This may mean that our normalization to the 3rd order K-shell lines of C V is off by several factors, thus resulting in an overprediction of these intensity of these lines. Despite this overprediction, the predicted intensity of the lines in question near 173, 182, and 189 Å is far too weak to account for the intensity of these carbon lines.

Figure 2 shows an expanded view of the spectral region near the three carbon features. The figure clearly demonstrates that the strengths predicted in our FAC model are vanishingly small. This rules out electron-impact excitation as the process forming these lines.

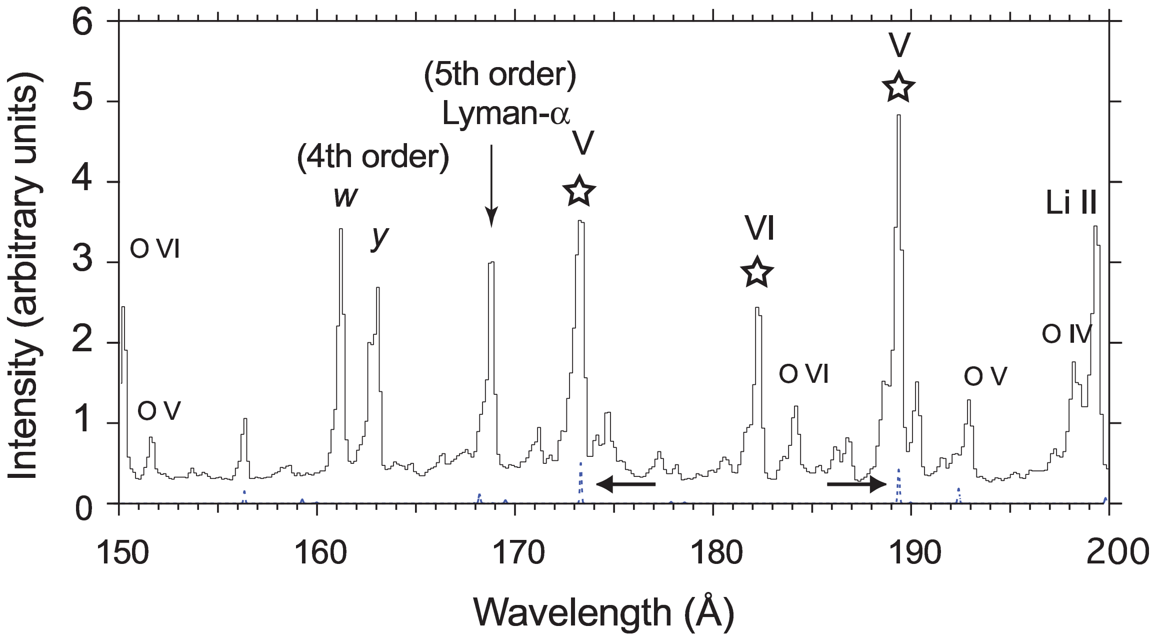

Figure 2. Inset of NSTX Shot 140324 showing comparison between calculated emission strengths via collisional excitation (blue dashed lines) vs. measured (solid line). Lines not identified to element are carbon; strong new carbon lines are marked with stars.

The strength of the new C V and C VI lines in our spectrum is indicative of non-equilibrium plasma processes, in particular, of charge exchange between highly charged carbon with neutral hydrogen. Charge exchange populates the n = 3,4 levels in carbon ions, and our two strongest lines, at 173.19 and 189.40 Å are both 4→2 transitions, while the feature at 182.23Å is a blend of 3→2 transitions. We are now undertaking calculations of the spectral emission due to charge exchange between hydrogen and bare and hydrogenlike carbon utilizing the Charge Exchange Spectral Synthesizer, CHESS [8]. CHESS predicts spectral emission patterns that match the observations well. These calculations are ongoing and will be presented in future work.

Acknowledgments
This work was performed by Lawrence Livermore National Laboratory and Princeton Plasma Physics Laboratory under the auspices of the U. S. Department of Energy under Contracts DEAC52-07NA27344 and DE-AC02-09CH11466 and supported by the U.S. Department of Energy, Office of Science, Office of Fusion Energy Sciences.

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